Climate change and landscape-ecological effects in the Western Mediterranean: future, present and learning from the past

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Zusammenfassung

Klimawandel und landschaftsökologische Folgen im westlichen Mediterranraum – Zukunft, Gegenwart und Lernen aus der Vergangenheit

Der westliche Mediterranraum ist eine vom globalen Klimawandel am stärksten betroffenen Regionen weltweit. Klimamodelle sagen einen starken Anstieg der jährlichen Durchschnittstemperaturen auf der Iberischen Halbinsel voraus. Bis zum Ende dieses Jahrhunderts wird mit einem Anstieg der mittleren Temperaturen um bis zu 5 °C gerechnet. Bei einem gleichzeitig starken Rückgang der Jahresniederschläge wird sich in Zukunft die Ressource Wasser drastisch verknappen und das bei einem derzeitigen Rekordwasserverbrauch von 200 Liter pro Tag und Einwohner. Bei Zunahmen von Dürren, Waldbränden, Sturzfluten sowie weiteren Umweltkrisen wie Grundwasserversalzung und -verknappung muss auch mit verschärften ökonomischen Krisen in der Region gerechnet werden. Instrumentelle Klimaaufzeichnungen der letzten hundert Jahre aber auch Geoarchive und archäologische Grabungen aus dem westlichen Mediterranraum belegen, dass klimainduzierte Veränderungen der Landschaft und daraus resultierte Umstellungen der menschlichen Aktivitäten auch in der Vergangenheit nicht die Ausnahme sondern vielmehr die Regel darstellten.

Klimawandel, westlicher Mediterranraum, Mensch-Umwelt-Beziehungen, Landschaftsökologie, Geoarchäologie

Abstract

The western Mediterranean is one of the regions in the world most strongly affected by global climate change. Climate models predict a strong rise in the mean annual temperatures on the Iberian peninsula. A rise of up to 5 °C is forecast by the end of this century. In combination with a concurrent strong reduction in the annual precipitations, in future there will be a drastic shortage of the resource water, and this at a current record water consumption of 200 litres per head of population per day. In combination with increases in the numbers of droughts, wildfires, flash floods, and other ecological crises – for instance saltwater intrusion and decreases in water availability – exacerbated economic crises in the region must be reckoned with. Instrumental climate records taken in the past one hundred years as well as terrestrial archives und archaeological excavations demonstrate that in the past, too. Climate-induced modifications of Mediterranean ecosystems and resulting changes in human activities are not the exception, but rather the rule.

Climate change, western Mediterranean, human response, landscape ecology, geoarchaeology

Western Mediterranean region: High sensitivity towards climatic oscillations

In terms of the climate, in summer the Mediterranean lies in the area of influence of the dry subtropical high. Winters, by contrast, are moist, the result of air masses transported by the prevailing westerlies. The dry summer subtropical climate of the Mediterranean has a distinctly high landscape sensitivity towards climatic shifts as a consequence. In particular, variations of the mean annual precipitation are associated with considerable landscape-ecological effects in the region. Decreases in precipitation lead to a diminution in the amount of average annual groundwater recharge, to reduced mean annual discharges, and to a general shortage of the natural resource "water". In the medium term, prolonged dry periods and increased fire activity in Mediterranean woodlands have resulted in an enhancement of xerophilous and fire-resistant species. Changes in the precipitation pattern also have serious consequences on relief development and the morphological processes. A sparse vegetation cover as the consequence of a prolonged dry period provides only insufficient protection against soil runoff in the case of intense rainfall events. Decreased mean precipitation in combination with high rain intensities are associated with high rates of sheet and linear erosion (Faust 1995; Ries 2006), potentially resulting in the complete loss of valuable soil cover. Conversely, the increase in mean annual precipitation may also result in locally raised rates of soil erosion, e.g. in regions with a high landslide risk (Zezere et al. 2005).

Climate change – The future Mediterranean climate

The Intergovernmental Panel on Climate Change (IPCC) published its fourth assessment report in 2007. In 2005, the concentration of the greenhouse gas carbon dioxide in the atmosphere reached a level of 379 ppm, a value demonstrably above that evidenced for the planet Earth in the past 650,000 years by means of ice cores (IPCC 2007). In the time since the first weather records were taken in 1850, the global temperatures have risen by 0.76 °C to 14.5 °C. Since 1870, the mean sea level has already risen 20 cm as a consequence of the thermic expansion of the water. In the past 25 years, the snow cover on the northern hemisphere has fallen 10 %. One global heat record is chased by the next: eleven of the past twelve years have globally been shown to be the warmest years since 1850 (IPCC 2007). While previous assessment reports have so far described only high probabilities of an impending

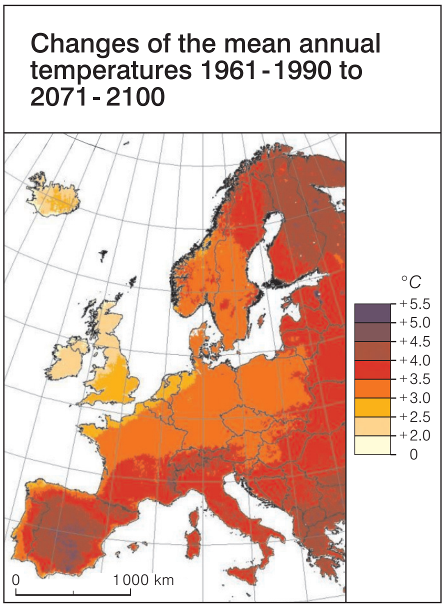

Fig. 1: Changes of the mean annual temperatures at the end of the 21st century in Europe in consideration of IPCC scenario A2 (1961-1990 in comparison with 2071-2100) – circulation model HadCM3
Source: PRUDENCE project (modified)

human-induced change in the climate, the current climate change is meanwhile considered "virtually certain".

What consequences does global warming have for the regional Mediterranean climate? Not all regions of the Earth are affected by global warming to the same degree. Compared with the global average, the temperatures in the inner tropics, for example, have risen only to a below-average degree. The temperatures in the high latitudes and in the subtropical Mediterranean, by contrast, have risen to an above-average degree. At the end of the 21st century, in Spain a rise in the mean annual temperature by as much as 5 °C must be reckoned with (Fig. 1), representing the highest rates of increase in the whole of Europe. And as if this were not enough, besides the strong rise in the temperature an above-average drop in the mean annual precipitation must be anticipated. This applies above all to the western Mediterranean, and to the Iberian peninsula in particular (Fig. 2). If one is to give credibility to the prognoses of the climate modellers, the

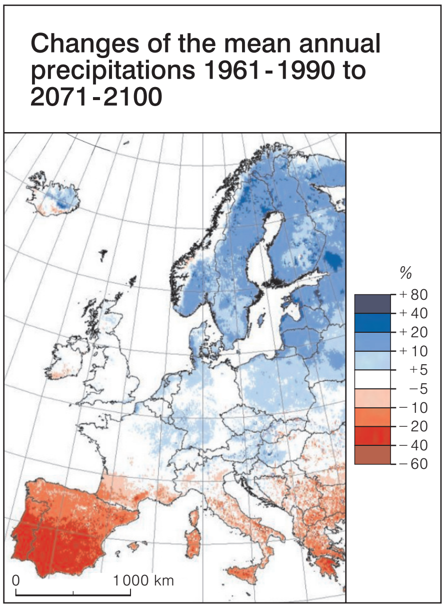

Fig. 2: Changes of the mean annual precipitations at the end of the 21st century in Europe in consideration of IPCC scenario A2 (1961-1990 in comparison with 2071-2100) – circulation model HadCM3
Source: PRUDENCE project (modified)

mean annual precipitation will drop by as much as 40 %.

Climate change – Future ecological and economical effects, taking Spain as an example

Due to the decrease in mean annual precipitation, the higher mean annual temperatures, and the additionally raised potential evaporation, the mean discharges in Spain shall decrease to a very strong degree (Tab. 1). Furthermore, a very strong rise in the incidence of drought and heat waves must be reckoned with. Both have fatal ecological consequences, which may also involve sensitive economic crises. This is particularly true for the low-in-precipitation Spanish Mediterranean region.

Due to the reinforced intensification of the Spanish agricultural industry since the country joined the EU at the beginning of the 1980s, and also as a consequence of the high water consumption in the tourism sector, matched only

Climatic Change in Europe

	Central Europe	Mediterranean
Mean temperatures	increase	very strong increase
Winter floods	strong increase	constant/ decrease
Inland flash floods	increase	strong increase
Mean annual discharge	constant	very strong decrease
Drought/ heat waves	increase	very strong increase
Periods of high fire risks	increase	very strong increase

Tab. 1: Climatic Change in Europe
Source: Alcamo et al. 2007

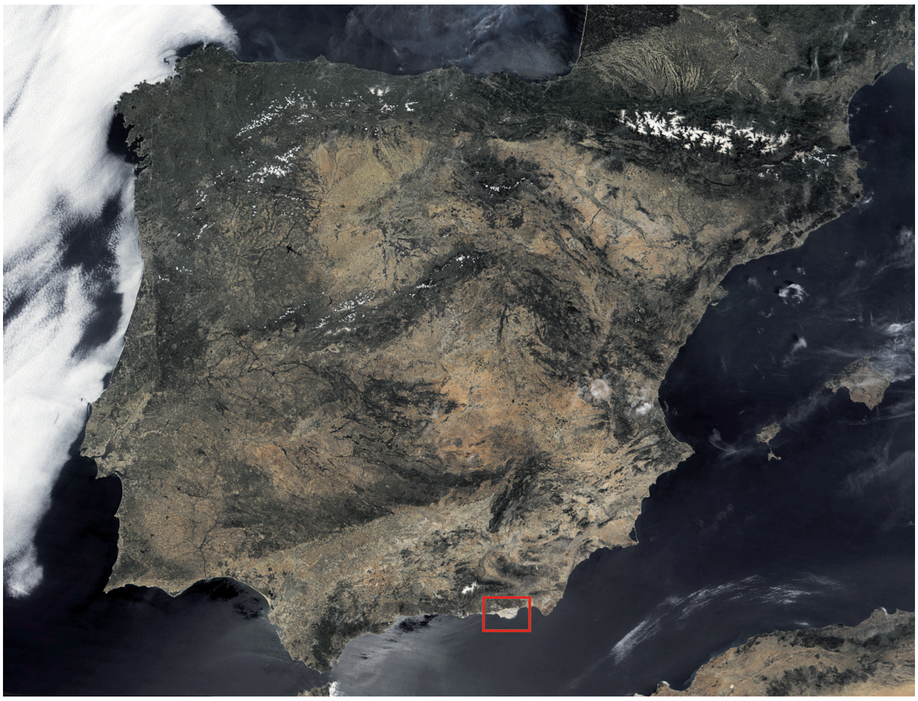

Fig. 3: Spring-time Terra/MODIS satellite image of the Iberian Peninsula. Snow fields can still be seen in the Pyrenees and the Sierra Nevada. The white area to the west of Almeria (red rectangle), by contrast, is the World's largest greenhouse horticultural area under plastic film. Fig. 4 shows a detailed magnification.
Source: NASA Visible Earth – Sensor Terra/MODIS

by Greece, it is particularly the low-in-water country of Spain that has the highest per capita water consumption in the whole of the European Union. At a value of over 200 litres per head of population, the daily water consumption in Spain is approximately 80 litres higher than that for Germany. Roughly 70 % of this water is used for the irrigation of agricultural areas. Figure 3 shows a springtime Terra/MODIS image of the Iberian peninsula. Snow fields are apparent in the Pyrenees and the Sierra Nevada. The white areas to the west of Almeria, however, do not show snow, but instead the world's largest vegetable-growing area, covered with plastic sheeting. The as-it-were tropical temperature conditions in southern Spain have resulted there in particular in a strongly export-oriented, irrigation-intensive agricultural industry (Tout 1990). In the hot but arid region of El Ejido (Fig. 4), the past three decades have seen the erection of 36,000 hectares

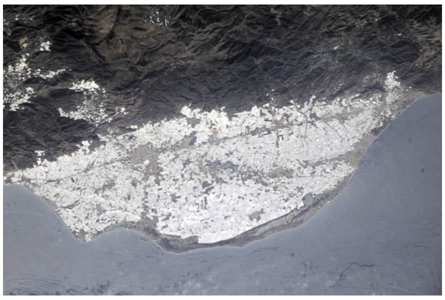

Fig. 4: The "El Ejido" horticultural region near Almeria: Already today it is not possible to sustain the high water demand from the arid region. The consequence: salination due to salt-water intrusion into groundwater aquifers.
Source: NASA Visible Earth – Sensor Terra/MODIS

of plastic-sheet greenhouse facilities. Even today, the high water consumption puts an extreme strain on the ever-dwindling natural resource of groundwater (Costa & Heuvelink 2000), which has led – not only in El Ejido, but also in numerous other coastal regions that are intensively exploited both agriculturally and touristically – to salt-water intrusion into groundwater aquifers (Kent et al. 2002). The water crisis in southern Spain caused by overexploitation shall deteriorate further still as a consequence of the water shortages arising from future climate change (cf. Fig. 2).

A taste of what is to come was experienced by the region surrounding the metropolis of Barcelona in spring 2008, with the northern Spanish region of Catalonia suffering the worst period of drought in over 50 years. The levels of the dam reservoirs in the hinterlands of the Costa Brava were down to 20 percent of their capacity. Stringent water-conservation measures in the daily water consumption notwithstanding, the five million inhabitants of the province stood just a short distance away from being supplied with water from tanker ships and trains. It was only the late rainfalls at the end of May and the beginning of June 2008 that brought provisional relief to the precarious situation. With the implementation of a 200-million euro programme, the Spanish government is now planning to construct a gigantic network of emergency water pipelines from the Ebro basin as a measure to defuse potential water crises in Catalonia in future. The neighbouring, richer-in-water regions in northern Spain, however, are massively protesting against these plans (Schulze 2008). The battle for water here has long since become part of the everyday political sphere.

Water is synonymous with life. Not only on the Iberian Peninsula, water is an essential resource in all sectors of the economy. The high above-average consumption of water in Spain can, however, be explained in particular by the high demand for this resource in the economically important sectors of agriculture and tourism. Already today water counts as a good in short supply and an at-risk resource. The country now faces further shortages of this resource due to future climate change.

There are as yet only limited definitive research findings regarding the landscape-ecological effects of climate change on Mediterranean woodlands. The currently available results from still-in-progress landscape-ecological research projects in the western Mediterranean area have so far focussed on methodological complexes and objectives (cf. del Barrio et al. 2006; Jurasinski & Beierkuhnlein 2006; Bürger et al. 2007). It must be anticipated that even minor fluctuations in precipitation variability and intensity will result in significant changes in soil moisture and discharge, which in turn shall have effects on water availability and subsequently also on physiological conditions and species distribution. This is particularly true for the regions in southern Spain, which already today are very arid (Puigdefabregas et al. 1999). According to recent model approaches, a climatic change in southern Spain will result in abrupt changes in the species distribution in woodlands, involving not only the spacial movement of entire phytoecological zones, but also and in particular their fragmentary transformation (del Barrio et al. 2006).

In addition to effects due to climate change, the aspect of the biodiversity of Mediterranean woodlands is particularly endangered by the ongoing influence of anthropogenic disturbance regimes, such as overgrazing and changes of fire frequencies (Fig. 5). In the North African Mediterranean woodlands in particular, the strong overgrazing can be reckoned to result in considerable losses in biodiversity (Jurasinski & Beierkuhnlein 2002). Models demonstrate raised incidences of natural fires due to anthropogenically induced forest fires in Spain (Benavent-Corai et al. 2007), which may become enhanced further still by the raised, climate-induced risks of drought (Gomes & Radovanovic 2008). Already in recent decades there has been a recession in the spatial distribution of mountain-

Fig. 5: Changes in fire frequencies – Human- and drought-induced fires in woodlands lead to changes in biodiversity. The distribution of fire-adapting species will increase in future Mediterranean woodlands.
Source: Archivo de la Consejeria de Medio Ambiente

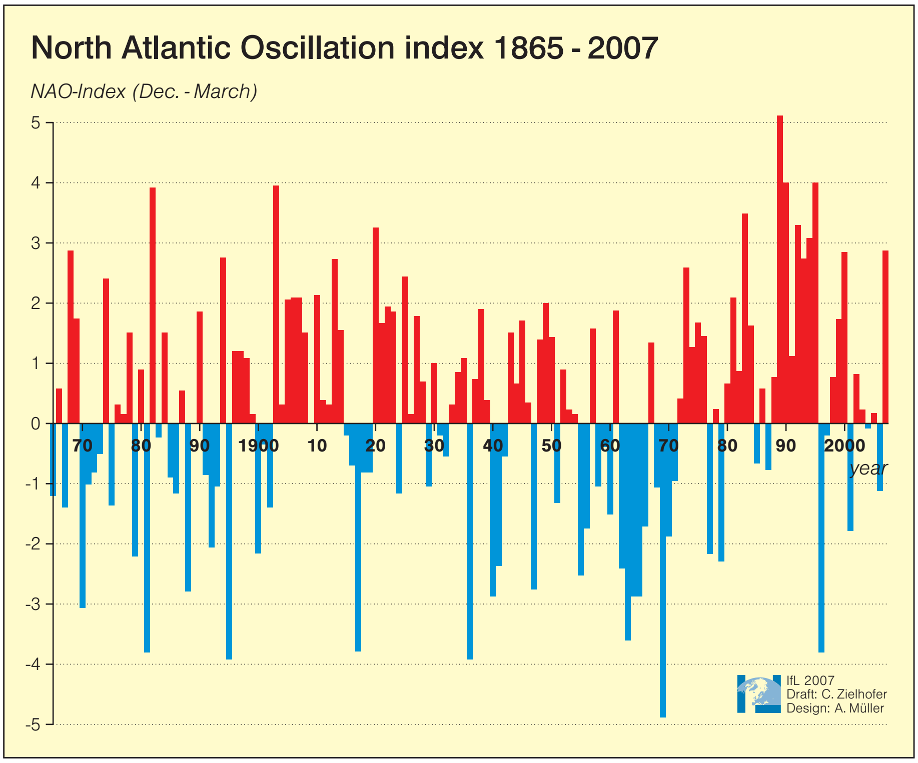

Fig. 6: The North Atlantic Oscillation index since the onset of the instrumental record in 1865. It is especially the winterly indices that are of relevance for the west Mediterranean mean annual precipitation, since most precipitation falls during the winter months. High indices lead to dry winters in the western Mediterranean.
Data source: www.noaa.gov

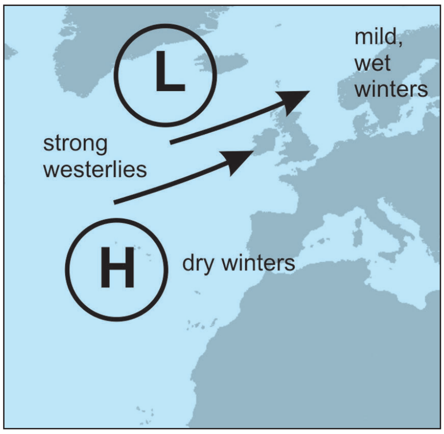

Fig. 7: Positive NAO index with high-pressure gradient between Icelandic low and Azorean high: Strong westerlies lead to mild and wet winters in Central Europe and dry winters in the western Mediterranean.

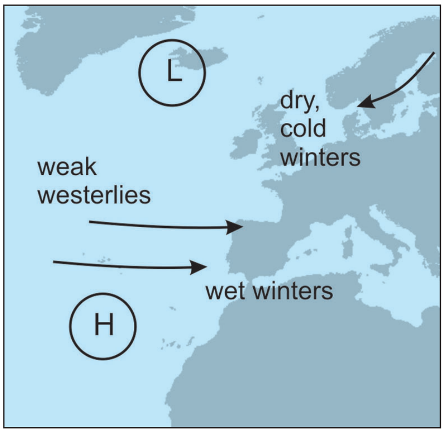

Fig. 8: Negative NAO index with low-pressure gradient between Icelandic low and Azorean high: Slight westerlies lead to dry and cold winters in Central Europe and wet winters in the western Mediterranean.

ous woodlands on the Iberian peninsula (Fulé et al. 2007). Furthermore, the increase in forest-fire frequencies has consequences for the landscape-ecological components "water" and "soil". Mayor et al. (2007) discuss post-fire hydrological and erosional responses of a Mediterranean landscape in southern Spain. Increases in fire frequencies lead to an exponential rise in the rates of soil erosion in catchment-scale research areas.

Current climate oscillations – Present water availability in the western Mediterranean

The past decades have already seen the implementation of extensive hydroengineering campaigns on the Iberian peninsula as a measure to ensure the continuous supply of water. This is exemplied not least by the construction of over 1,400 reservoir dams. The aim of these measures, however, has not so much been to counteract the future decrease in rainfall, but rather to form a counterbalance regarding the high seasonal and interannual rainfall variability. Particularly the arid to semiarid regions of the western Mediterranean are characterized by a strong interannual rainfall variability. While this is indeed usual in arid climates, on the Iberian peninsula this phenomenon is amplified by the North Atlantic Oscillation (NAO) phe-

Fig. 9: Location of the three main rivers in Iberia and their catchment boundaries.
Source: Trigo et al. 2004 (modified)

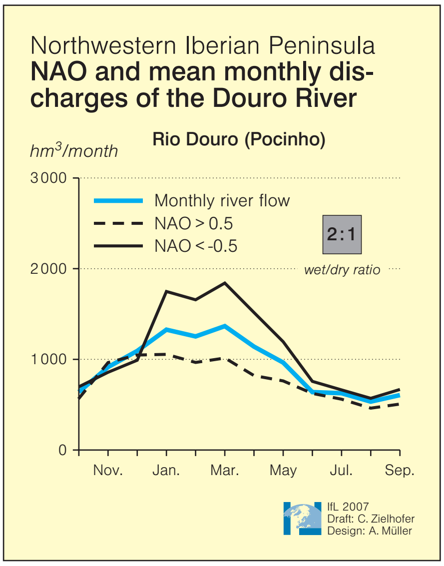

Fig. 10: Monthly discharges of the Douro River in the subhumid northwestern Iberian penisula. The blue line indicates mean monthly discharges, the black line mean monthly discharges in years with an NAO index above 0.5, and the dashed line mean monthly discharges in years with an NAO index below -0.5. The ratio between discharges in wet (negative NAO) and dry (positive NAO) years is 2:1.
Source: Trigo et al. 2004 (modified)

nomenon. This term is used to describe atmospheric pressure anomalies in the eastern North Atlantic realm, which feature annual and superimposed decadal-scale winter-climate oscillations (Fig. 6). The NAO is a large-scale seesaw in atmospheric mass between the subtropical Azorean high and the polar Icelandic low. The corresponding index varies from year to year. The higher the pressure gradient between Icelandic low and Azorean high (positive index), the more intense the prevalent westerlies. These result in mild and wet winters in central Europe and dry winters in the western Mediterranean (Fig. 7). Conversely, a negative index with a low pressure gradient leads to dry and cold winters in central Europe and wet winters in the western Mediterranean (Fig. 8).

The effects of the North Atlantic Oscillation on the present water availability in the western Mediterranean can be exemplarily read off in the form of variations in mean monthly discharges of principal Iberian rivers. The western Iberian peninsula is drained by the Douro, Tejo, and Guadiana Rivers (Fig. 9). The catchments reveal a gradient from subhumid to semiarid Mediterranean climate from north to south. Figure 10 shows the mean monthly discharges of the Douro River. The blue line shows the maximum discharges during the winter season, which is typical for Mediterranean river systems. However, the dashed and black lines indicate differences in mean annual discharges in positive NAO years (dry) and negative NAO years (wet). The ratio between discharges in wet and dry years is approximately 2:1. Figure 11 shows the mean monthly discharges of the semiarid Guadiana catchment. Here, the ratio between wet and dry years is approximate 8:1, readily illustrating that the present water availibility in the already arid regions of the southern reaches of the Iberian peninsula deteriorates dramatically in dry years.

Learning from the past: Environmental archives reveal abrupt landscape response to past climate changes

Taking the abrupt reaction of the precipitation and discharge pattern with respect to present climate oscillations (NAO, see above) on the Iberian peninsula, future climate changes can be anticipated to result in short-term shifts in fluvial dynamics and water availability, with the resultant dire consequences for all landscape-ecological system components. In this connection, we are well advised to look back into the past: in recent years, an increasing number of high-resolution palaeoecological archives from the western Mediterranean have been examined. Climatic param-

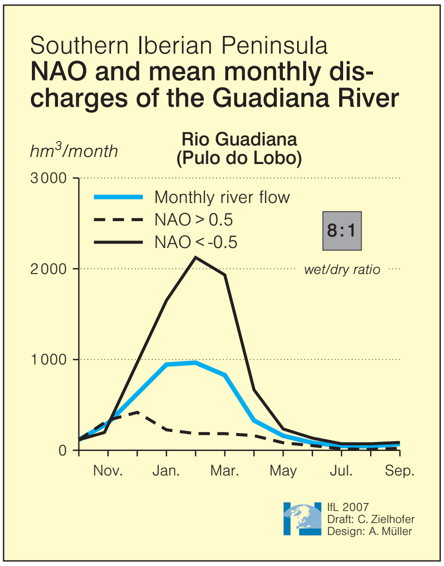

Fig. 11: Monthly discharges of the Guadiana River in the semiarid southern Iberian Peninsula. The blue line indicates the mean monthly discharges, the black line mean monthly discharges in years with an NAO index above 0.5, and the dashed line mean monthly discharges in years with an NAO index below -0.5. The ratio between discharges in wet (negative NAO) and dry (positive NAO) years is 8:1.
Source: Trigo et al. 2004 (modified)

Fig. 12: The photo shows fluvial sediments from the Mellegue River in central Tunisia. Fluvial archives document periods of increased sedimentation rates due to enhanced flooding and periods of soil formation due to minor flooding. In the fluvial exposure, fossil soils are detectable by its reddish to humic (grey-black) colour and aggregated soil structure. Upwards, fossil soils reveal a sharp shift to the covering sediment layer, whereas downwards colour and soil structure show a diffuse transition to the underlying sediment layer.
Photo: F. Haubold 2002

Fig. 13: Fluvial activity date: Several thousands of years ago, a fragment of charcoal was transported by the river before it was buried by fluvial sediments during the immediately ensuing deposition process. This protected the charcoal fragment from erosion and preserved it for posterity (environmental archive). Determination of the age of the charcoal fragment by the radiocarbon-dating method (14C method) yields a date that – under consideration of the methodic inaccuracy (approx. ± 50 years) – indicates a period of flooding (fluvially active phase).
Source: Zielhofer & Faust 2008

Fig. 14: Landscape stability date: When fluvial sediments on the surface of a floodplain are no longer flooded with water, the result is the formation of an initial soil in the topmost layers. The activity of soil organisms during the soil-formation phase results in the formation of organic acids in the sediment. When this soil is then covered by new sediment layers in a subsequent flooding phase, the organic acids in the sediment remain archived and can be dated using the 14C method. A 14C age of pedogenetic organic material within the floodplain indicates landscape stability or periods of minor flood dynamics.
Source: Zielhofer & Faust 2008

eters derivable from speleothems and marine cores are evidence of substantial and suddenly onsetting variations of mean temperatures in the course of the last ten to hundred millennia. The motors behind these climatic variations were in many cases orbital forcing, such as variations in solar radiation or sunspot activity. These result in regular climate cycles of several ten millennia (e.g. Milankovitch cycles), several millennia (e.g. Bond cycles), or even only several decades and years (e.g. sunspot cycles), cycles that may overlap and mutually amplify each other. On top of this come natural climate variations due to oceanic "climate engines" such as the Gulf Stream and the North Atlantic Deep-Water formation. There is evidence from the past of amplitudes of abrupt changes in temperatures that may serve as indicators for future scenarios. In other words, even without the influence of mankind, during the

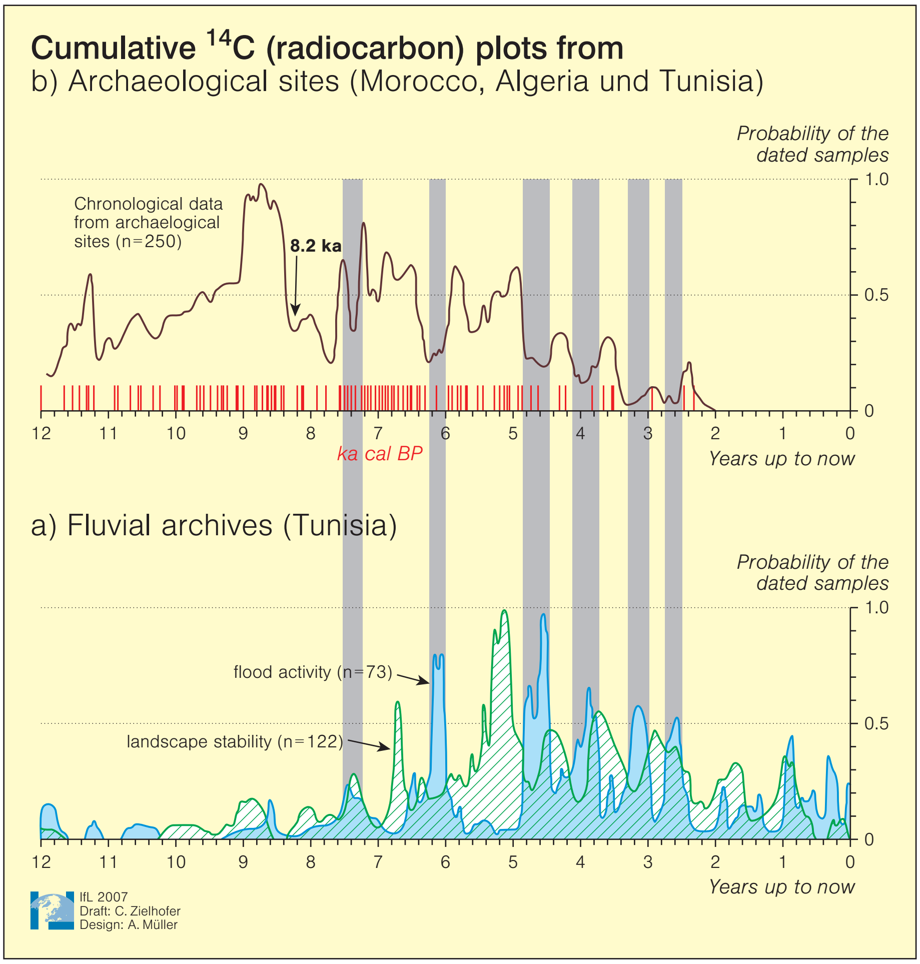

Fig. 15: Cumulative 14C (radiocarbon) plots from a) Tunisian fluvial archives and b) archaeological sites of Morocco, Algeria, and Tunisia. The x-axis shows the time period of the last 12,000 years. The plots feature the occurrence of individual 14C ages from fluvial archives and archaeological sites. The greater the amplitude of the curves (y-axis), the more frequently are the 14C dates to be found in a certain timespan. In the lower part of Figure (a) the two curves exhibit a strongly countercurrent character. Floodplain soil formation ("stability dates") and flooding ("activity dates") are mutually exclusive. This speaks in favour of the reliability of the independent datasets. The upper 14C plot (b) of archaeological data is in opposite cyclicity to the plot of "activity data".
Source: Zielhofer & Faust 2008; Zielhofer et al. 2008

last glacial period (Weichsel: 110,000 to 12,000 years before present), but also in the current warm period (Holocene: 12.000 to 0 years before present) there have repeatedly been strong decreases and increases in temperatures (e.g. Cacho et al. 2001; Combourieu-Nedout et al. 2002; Moreno et al. 2005).

Similar to the prognoses for the future, the changes in mean temperature in the western Mediterranean area in the past have also involved variations in the mean precipitation, resulting in considerable landscape-ecological consequences. In the course of the Holocene, there is evidence in northern Africa (e.g. Stevenson et al. 1993) and southern Spain (Fletcher et al. 2007) of abrupt reactions by the woodland ecosystems to short-term changes in climate humidity. During humid phases western Mediterranean pollen records indicate an increase of deciduous forests, whereas short-term climate dry periods come along with changes to more xerophilous and fire-resistant species. Beside changes in vegetation, Benito et al. (2003) also document short-term increases of extreme flood events on the Iberian peninsula due to cyclic North Atlantic cooling during the last 10,000 years. They link cooling with more humid conditions in the western Mediterranean.

Fluvial archives may document geomorphological responses to past climatic oscillations and shifts (Fig. 12, 13 and 14). Here, Zielhofer and Faust (2008) present a dataset of Holocene radiocarbon dates from Tunisian floodplain deposits to identify climate-driven phases of increased fluvial activity and phases of decreased flooding. They create two radiocarbon (^{14}C) plots from Tunisian fluvial deposits: the former represents “activity dates” indicating phases of increased fluvial dynamics, the latter documents “stability dates” showing periods of soil formation and enhanced landscape stability within the floodplain and the catchment. Due to geomorphological considerations, activity dates and stability dates should be mutually exclusive. Figure 15a shows the two plots of activity dates and stability dates that feature amplitudes of opposite cyclicity. The plots show that the Holocene fluvial history of Tunisia is characterized by centennial-scale changes in flooding, indicating a high sensitivity of the catchment towards rapid shifts in climate (Zielhofer & Faust 2008).

Learning from the past: Archaeological archives reveal abrupt human response to past climate changes

Cretaceous and Jurassic limestone in the eastern Rif Mountains of northeastern Morocco reveals a high potential for the creation of caves and rock-shelters. These were occupied by prehistoric societies to use the arid to semiarid environment for hunting and gathering. Remnants of these palaeolithic and neolithic societies (e.g. artefacts, bones, molluscs) are well-preserved in the caves and rock-shelters and reveal an excellent archive of past human occupation. Since the

Fig. 16: Ifri n'Ammar in northeastern Morocco: For some years now this cave has been the site of excavations by the German Archaeological Institute. The archaeological layers are rich in Epipalaeolithic and Palaeolithic artefacts. This cave is a key site for prehistoric research in North Africa.
Photo: Eiwanger 2004

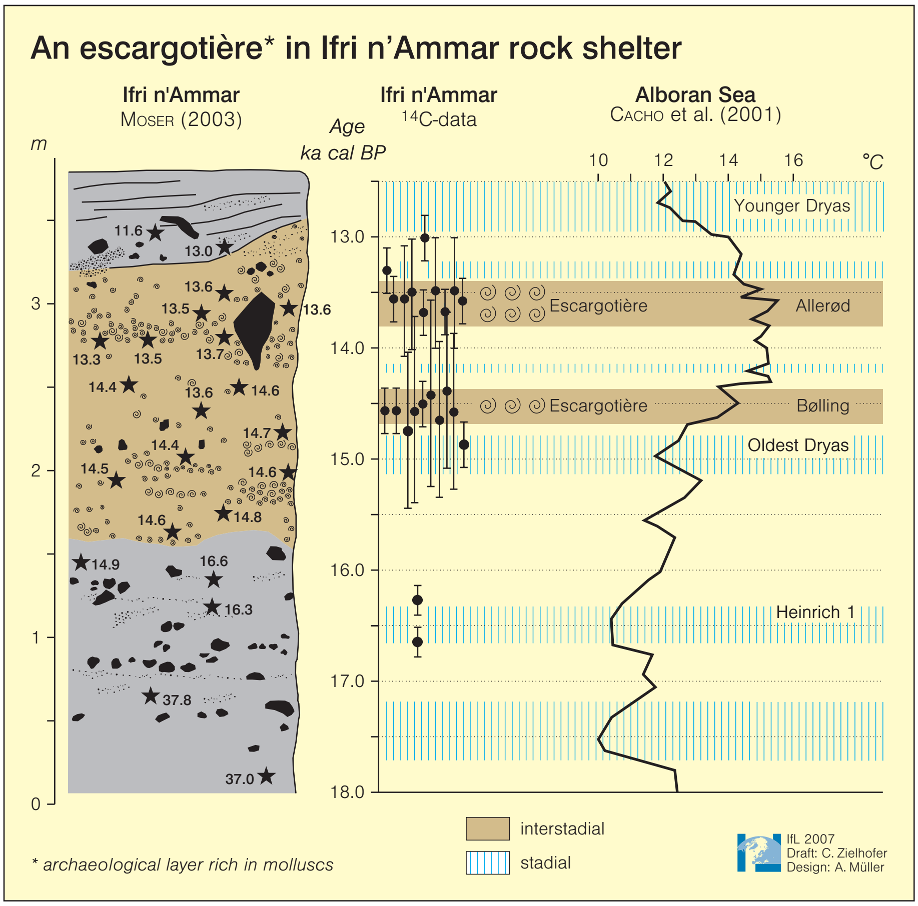

Fig. 17: An escargotière (archaeological layer rich in molluscs) in Ifri n'Ammar rock shelter. The radiocarbon dates of charcoal remnants in the escargotière indicate a signal of climate-driven land-use pattern. The rock shelter was used for the huge consumption of molluscs only during the late Glacial Bølling-Allerød warm period.
Source: Cacho et al. 2001 and Moser 2003

1990s these archaeological sites have been under excavation by an international geoarchaeological research group (cf. Mikdad et al. 2000; Moser 2003). One of the most spectacular excavations is the Ifri n'Ammar (Fig. 16), a rock shelter with several meters of Epipalaeolithic and Palaeolithic layers. In the upper part of the Ifri n'Ammar archaeological sequence a mighty escargotière (debris of consumed snails) is preserved. Taking the distribution of ^{14}C data from this escargotière (Fig. 17) as an indicator of temporal human activity, two phases may be observed. Two peaks are visible in the figure, matching the late glacial Bølling and Allerød warm periods. The rock shelter was used for the huge consumption of molluscs during these two periods of favourable climatic conditions. The Bølling and Allerød periods are characterized by an increase of 3 °C in the west Mediterranean region (Fig. 17; Cacho et al. 2001). In semiarid Mediterranean North Africa, the late glacial increase in temperature was associated with more humid conditions (Zielhofer et al. 2004). Here, the Ifri n'Ammar archive reveals that an ecological shift in the landscape is indirectly visible by the pattern of change in the use of land by prehistoric hunter-gather communities.

Regarding a compilation of all available ^{14}C archaeological data from Mediterranean North Africa, the amplitude of the plot (Fig. 15 b) indicates that prehistoric societies seemed to be very sensitive to environmental shifts through time. Chronological gaps or breaks in the archaeological exposures often correlate with past environmental changes. Further research may show whether there are causal relations or not. Climatic impact causes environmental changes and, therefore, human responses such as shifts in prehistoric land use or occupation are probable.

Conclusions

Present hydrological, landscape-ecological and palaeoecological findings indicate that the western Mediterranean region has been influenced by short-term climatic changes. Terrestrial archives, marine cores and instrumental records reveal temperature changes and brief changes in humidity in the course of present climatic oscillations and during the past. Shifts in humidity cause landscape-ecological responses such as changes in vegetation cover, changes in runoff, or changes in wildfire frequencies. Archaeological archives reveal responses of prehistoric hunter-gatherer societies to climatic signals, too.

Regarding future climate change, the western Mediterranean will be affected by an increase in mean temperatures higher than the global average. This is shown by present climate models. Warming is associated with strong decreases in humidity leading to brief ecological and economical consequences in the region. Learning from the past: terrestrial and marine records indicate that past climatic changes in this region are not the exception, but instead the rule.

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